TECHNICAL MEMORANDUMS

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

No. 786

THE FORMATION OF ICE ON AIRPLANES

By H. Noth and W. Polte

Luftwissen
Vol. II, No. 11, 1935

Washington
February 1936

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL MEMORANDUM NO. 786

THE FORMATION OF ICE ON AIRPLANES*

By H. Noth and W. Polte

SUMMARY

The greatest drawback of bad-weather flying is the ice hazard. Technical literature contains numerous accounts of the causes of icing and the means to prevent or to remove such ice deposits from aircraft, but practical experiences have rarely been made public. The present report represents the problem from the point of view of the pilot and the meteorologist. Their experiences prove the ice deposit to be first and foremost a navigational problem and only secondarily a question of de-icing devices. With correct utilization of the meteorological information by the flyer, ice hazard can in many cases be minimized, if not avoided, altogether.

INTRODUCTION

The reason that icing of aircraft had not produced more difficulties in the past was that flying was generally very restricted during the cold seasons of the year; besides, prolonged flying in clouds did not start until of comparatively recent date. With the arrival of instrument flying, icing difficulties have assumed abnormal proportions.

All aircraft are exposed to the ice hazard - balloons as well as airplanes. Admittedly, the degree of ice formation varies, depending largely on the speed of the aircraft relative to the air, which practically excludes free balloons. They can, in the worst cases, accumulate no heavier coating of ice than covers the ground, unless the balloon pilot is a very poor navigator and remains longer within the ice-forming zone than the time necessary for glazing the ground with a heavy covering of ice.

*"Über die Vereisung von Luftfahrzeugen." Luftwissen, November 1935, pp. 304-311.

ICE FORMATION AND CHARACTER OF ICE DEPOSITS

The meteorological and physical conditions and processes under which ice may accrete on airplanes are extremely complex and have never been satisfactorily explained.

How does it take place? The most important and most frequent case occurs when flying in clouds at below freezing temperatures. These clouds consist of very minute water droplets whose temperature is likewise below zero; that is, they are supercooled and are still in liquid form. Supercooled water generally freezes at the instant of collision or contact with ice. Both possibilities are almost always present when an airplane or airship flies through such clouds. Since supercooled water droplets remain liquid down to -20°, the possibility of ice accretion exists. This has been proved in practice. The most frequent and heaviest ice deposits are observed between 0 and -6° C. The start is not contingent upon zero temperature; it may start some degrees above, or even below.

The depth and acceleration of the ice deposit is governed by the following: As the rate of fall of the water droplets varies between 0.001 m/s (0.003 ft./sec.) and, in the extreme, 7 m/s (23 ft./sec.), depending on size, whereas the airplane speeds range between 40 and 100 m/s (131 and 328 ft./sec.), the air may, during this formative process, be visualized as filled with stationary water droplets. According to that, the rate of ice formation depends upon the speed of the airplane. To illustrate: On an airplane flying at 100 m/s, ice formation occurs twenty times as fast as on the ground, which supercooled droplets strike vertically at a speed of 5 m/s (16.4 ft./sec.).

The thickness depends on the existing volume of supercooled droplets per cubic meter of air as well as on the distance flown by the airplane in the ice-forming zone; that is, the time during which the icing process lasts and the particular airplane characteristics.

Another decisive factor is the angle at which the drops strike the particular part of the airplane - as the leading edge of the wing, for instance. Expressed in mathematical terms, the thickness of ice deposit in supercooled large-droplet rain is:

$$E_f = \gamma_w \, v \, t \sin \delta \, C$$

whereby E_f = ice deposit per unit of area, γ_w = water content per unit of volume, v = velocity relative to air, t = time, δ = angle of impact, and C = constant.

This brings us to the problem of the character of ice deposits. The character of ice varies according to the basic conditions for ice accumulation; the findings on its formation, shape, and color are still very much at variance and reveal changes from one form to another, thus making a description difficult. The suspended water droplets may be so small as to be blown away by the current of the airplane, in which case no appreciable ice deposit will form. Quite possibly the ice accretion is bound up with the boundary layer and the size of the droplets. Even at the highest speeds, a velocity potential from the wing surface to the free air stream must exist. The potential will be highest - i.e., the participating air layer will be thinnest at the points where the air stream strikes the surface at an angle of around 45°. Very small water droplets of 1/1000 or 1/10000 mm will flow around a wing like air molecules and also past the boundary layer, acting as air cushion, so that contact with the surface - i.e., ice formation - is avoided. Starting with a very definite size of droplet, they are able, due to their mass inertia, to break through the boundary layer at the points of 45° of angle of impact, and to adhere. If the drops become larger they may, even on impact at more than 45 to 90°, penetrate the thicker boundary layer and effect the deposit directly on the the front side of the body. It was frequently observed that when the ice deposit was light, it usually started at a certain distance from the leading edge of the wing.

From the various phenomena, three types of ice deposits may be differentiated:

a) The ice has a glassy - almost transparent aspect. The surface is comparatively smooth. The form change on exposed parts of an airplane is fairly small. This ice is probably formed when an airplane, in or below clouds, encounters only supercooled water droplets or supercooled rain. If supercooled water droplets of various sizes strike an airplane simultaneously, for instance, in supercooled rain from an upper cloud layer onto the one below, through which the airplane is flying, the surface of the ice deposit will be rougher and less symmetrical. Depending on size and rate of fall of droplets, an airplane part becomes more or less covered with ice up to one-third of its section, starting from the leading edge (fig. 1). This kind of ice is quite tenacious, although it still can be knocked off with a hard object.

b) The ice is milky and not very transparent. The surface is rough and frequently reveals a granular or crystalline-brittle structure. The accumulation grows very rapidly on the leading edge, forms a continuously growing bulge with a peculiar tendency to spread more toward the sides than the front, thus building up a fairly broad area (fig. 2).

The form change is considerable and its effect on airplane characteristics and performance, very profound. The ice is probably formed in a cloud by supercooled water droplets and simultaneous solid precipitation. Depending on size and kind of solid precipitation, the surface may be covered with small hump-like accretions, to which the supercooled droplets cling and form a point in opposite direction to the air stream. The naturally granular surface, overlaid with the sharp-nosed mass (like a circular saw blade), gives the whole its identifying roughness. This ice accumulation grows very rapidly when the temperatures hover around zero. The tenacity of this form of ice is not great because the parts covered with it are not so thickly coated.

c) This type - unlike in formation, thickness, and shape - is mostly observed at temperatures of -10° or less. It is no glassy deposit but rather a crystalline, snow-like coat, building up in small amounts on the leading edges. The form change is slight. They are rather pointed accumulations in the concentration zone of the airplane parts exposed to the icing (fig. 3). The puzzling fact is that the propellers show a deposit extending from the hub almost to the tip. Its tenacity is great. It cannot be broken loose without damage, but must be thawed off.

Other than these cases with which the pilot generally comes in contact, there is the peculiar deposit of snow or rime: An airplane flies in or below the clouds in a stratum of a few degrees above zero temperature. If snow of large flakes happens to fall (it is known that a snowflake can fall approximately 100 m (328 ft.) in a layer of over 0° without completely melting), it sticks to the leading edges. This is followed by a continuous process of freezing and thawing. The amount of deposit depends upon the humidity and temperature of the zone through which the airplane is flying. An eventual evaporative cooling may at any time lower the temperature on the leading edge enough to cause the deposit to freeze and build up.

SPECIAL CASES

It may also happen, although very rarely, that an airplane becomes coated with a light rime deposit of barely visible thickness at very great heights, in the so-called "ice-needle" clouds, or even in a cloudless sky. It occurs when the airplane is severely cooled off in cold layers and then suddenly enters a warmer air mass of higher humidity, as a result of which it becomes befogged like spectacles. Rime may also form, as a result of ice supersaturation on an airplane covered with a very thin ice layer. Air which is still transparent but almost saturated with water vapor, itself precipitates ice on ice or on rime, although it does not give off any of its water-vapor content on water or a dry airplane.

Dr. Reidat, the directing meteorologist of the Berlin Aviation Weather Bureau, where the daily program includes two aerial soundings to 5,000-6,000 m (16,400-19,685 ft.), reports the following observation: It is frequently noted that supercooled water droplets do not immediately freeze on striking the airplane. The supercooled water first forms a liquid coating which runs off in drops (water and airplane certainly have temperatures below 0°!), but the supercooled water almost invariably freezes when the airplane approaches the top of the cloud, revealing blue sky above.

During the ascent, the airplane is a little warmer - at the most, as warm as the air. The drops are not further cooled off on contact. On convergence of the drops, the surface of the water diminishes, the surface tension decreases; the drop receives rather than gives off energy. The marked decrease in relative humidity usually prevailing at the upper cloud level causes a rapid evaporation accompanied by cooling, which instantly freezes any water found on the wings or tail surfaces. During descent and re-entrance of the cloud, the supercooled droplets freeze instantly as soon as they strike the now existing ice deposit on the airplane. Then the ice deposit builds up quickly, even in sub-zero zones which before had revealed none.

Ice formation at above-zero temperatures has been conclusively proved in rapid descent, in which the airplane was invariably a few degrees colder than the air around it.

On the other hand, ice may also form during prolonged flight at the same height level where the temperatures are above zero. The necessary basic condition is, of course, a dry layer of air upon which rain falls from above. The evaporation of the liquid coating clinging to the surface of the airplane then causes a cooling of several degrees. Accordingly, the airplane surface preserves, so long as it is moist, a subtemperature in which any drop striking it, freezes. These drops of water are, because of the fall and the evaporation in dry air, usually colder than the air and, in many cases, already supercooled. Naturally, such deposits stipulate temperatures up to about +3° C. Such conditions being no rare occurrence, it is certain that many reports on ice formation can be attributed to this cause. Of course, it is hard to prove them. Even so, many times the pilots have reported ice formation at above-zero temperature but a conclusive statement is impossible, owing to the difficulty of ascertaining the exact temperature condition; for the thermometer itself becomes damp and so may record a too-low temperature as a result of the evaporative cooling, when the free atmosphere is actually much warmer.

There is the case of two airplanes flying at the same time from Stettin to Berlin. One revealed no trace of ice, whereas the pilot of the other was barely able to land his ice-coated airplane. The two had flown close together although not exactly at the same height.

The cause of this rare occurrence lies in the peculiar character of the temperature grading (fig. 4). Owing to ever-present intermingling of the lower strata in wind, during which air is lifted up and thereby cooled off, the temperature becomes almost invariably colder for several hundred meters (200 to 600 m (656 to 1,968 ft.) in winter). In this particular case the temperature at 350 to 450 m (1,148 to 1,476 ft.) was below zero. The general rain falling at the time was supercooled in this region and consequently froze to the airplane. Unfortunately, the pilot had to pick this very altitude and hold it during the whole flight. Either 100 m (328 ft.) higher or lower would have carried him into the layer which his partner had accidentally chosen so wisely.

EFFECT OF ICE FORMATION

What are the changes caused by it? On airships, it is the readily noticeable increase in weight - considering that an ice crust 5 mm (0.2 in.) thick is equivalent to 5 kg/m^2 (1.02 lb./sq.ft.) loading. Such a load alone may lead to disaster (Nobile's polar flight). Even rapidly ascending and descending stratosphere balloons may become heavily coated with ice which, as nonjettisonable ballast, makes any predetermined dischargeable ballast reserve extremely doubtful.

On an airplane, the conditions are totally different. The ice accretion is first noticeable on the leading edges of exposed parts, such as struts, braces, tail, and wings. Parts having small profiles offer the best occasion for observing its start and growth. The effect on wings, engine, propeller, and instruments is as follows: The more or less extensive form change of the wing structure vitiates the lift and drag coefficients - which may become so bad that the airplane is unable to stay aloft even with full throttle.

The weight increase is of secondary importance, although it is uncomfortably noticeable in banking. Accidents have been recorded as the result of sideslipping with ice-caked airplanes in otherwise perfectly harmless banks. On aerodynamically well-designed airplanes, the condition of unfitness occurs comparatively early. The form changes on the individual parts cause oscillations, starting on the wires, wing tips, and tail. At very high speed these oscillations, occurring usually very suddenly, may lead to failure of the particular parts and to accident.

The effect on airplane stability is altogether different. Nose- and tail-heaviness have been observed, as well as torsion, about the longitudinal axis. The reason lies perhaps less in the shifted center of gravity than in the changed air flow on the tail, elevators, and their balance. The efforts necessary to equalize these changed flight characteristics by appropriate control reversal, may become so great that the pilot alone is unable to cope with it for any length of time.

The deleterious effect on the flight characteristics is accompanied by diminished flight performance, which depends on the thickness of the ice coating.

In judging the effect on the power plant, we must differentiate between liquid- and air-cooled engines. On the former, the engine itself is rarely affected, but its radiator shutters, when fitted in front, freeze into one surface, which causes the engine to run hot. On air-cooled engines, the entire carburetor assembly is affected. Ice may form on or in the suction scoop; if fitted with a screen, it quickly becomes coated with ice. The result is a different fuel-air mixture due to lack of air, the engine runs irregularly, and the r.p.m. finally decrease. With throttle valves frozen, the pilot is unable to operate except with force, which may result in breakage.

The effect on the propeller is unfavorable when the ice itself is thrown off irregularly. This induces severe oscillations as a result of loss of balance. The slow-turning propeller of the geared engine is, in this respect, even more objectionable because the gears amplify the disturbances. Amplitudes as high as 50 cm (19.7 in.) on the bracing wires of high-wing monoplanes with a corresponding transfer to the wing tips, have been noted.

Cable guides outside of the fuselage freeze, especially on the guide in the fiber bushings; likewise the reverse control levers.

The sliding windows of enclosed cockpits may freeze so tight as to prevent operation when trying to land.

Disturbances on oil tank and crankcase vents occur when protruding beyond the cowling.

Externally mounted venturis for driving the turn indicator Sperry horizon, and of the speed indicator are particularly susceptible to icing. Any eventual freezing of the formed condensed water may also cause disturbances.

Unless protected, the antenna weight and the fair-lead become coated with ice, which is soon noticeable on the drop in energy. Breakage of the fair-lead itself has occurred more rarely. Even fixed antennas are affected. Transverse antennas soon start to oscillate, snap, and may become entangled in the tail. Even the longitudinal fixed antenna requires some protection. Air-driven light generators are affected in the same manner. The impellers tear off as a result of loss of balance, or run hot in the bearings. The oscillations and vibrations of the whole assembly may even shake it loose from its frame and cause damage.

The structural material and design of the flight instrument is of importance only in so far as concerns the start of ice formation. After the initial coating, the growth is practically identical on all airplanes. Monoplanes with thick wing sections are not as readily coated as biplanes with thin wing sections, for example. Metal airplanes react differently from fabric-covered airplanes or those with wooden wings. The surface condition has a certain effect on the start. For example, seams or rivets on the front spar favor the ice deposit.

The question as to how thick the ice deposit may build up before becoming disturbing, can only be answered approximately. A 1- to 2-centimeter (0.3937 to 0.7874 inch) coat of ice produces appreciable changes in airplane characteristics and performances. Type of airplane and kind of ice also play a role. Rough ice with its rough surface, is worst of all. Some cases observed on older design types revealed ice coatings of more than 5 cm (1.97 in.) thickness, while especially exposed parts were coated to a depth of 10 cm (3.94 in.). Here the limit of flying had been reached.

The time necessary to form a heavy deposit of several centimeters also varies quite considerably and depends altogether on the water content of the air. There are cases on record when the airplane, after 5 or 10 minutes' flight, had become so coated with ice as to make a forced landing immediately imperative. Contrariwise, flights lasting from one to two hours, have been made in clouds of low water content and still the ice deposit did not exceed 2 cm (0.7874 in.) in depth.

WEATHER CONDITIONS DURING ICE FORMATION

Ice may form in any weather and in any cloud in which the temperature is below freezing. It forms fastest in cumuli, strato-cumuli, and cumulo-nimbus. Clouds in which the water vapor is still condensing, cause heavier ice; this consequently applies to all clouds lying above an entering, or in an overrunning, air mass. It does not necessarily require precipitation from the cloud. (See figs. 5, 6, and 7.)

The most dangerous case occurs in low, cold air, although in a different manner. Warm air either blows very severely on stationary, flat, cold air masses or flat, cold air pushes violently below warm air masses. The first case is illustrated in figure 5. The synoptic map shows a "low" over Iceland, one wedge stretching over Holland as far as Bohemia. Warm ocean air from the southwest and cold air from the polar continent meet on the axis of this wedge. The cold air stays on the ground and the warm air passes over it. The result is a cold-air wedge on the ground, rising from about 100 m (328 ft.) up to 1,100 m (3,609 ft.), and containing air of less than 0°, and supercooled rain at that. Over it lies air of above zero, although in the warm air above 1,100 m, sub-zero temperatures also exist (fig. 7). Snow or rain from the uppermost cloud layer falls on the warm air and the snowflakes melt. The rain then falls in the lower cold-air layer, whose temperature is several degrees below zero; it supercools and the drops striking the airplane, freeze instantly.

Figure 7 shows the frostless layer, in form of a continuously thinner wedge, pushing far beyond the cold air. Taking advantage of these conditions through meteorological vertical navigation, enables the flyer, in collaboration with the consulting meteorologist, to find the harmless zone. Three rules must be observed: The ice-forming weather condition is the same as for the summer thunderstorm - cyclonic wedge (called the heart of the thunderstorm in summer) with powerful pressure rise on the west side (fig. 6). It is the atmospheric condition of the change from frost to thawing weather. The average slope of the overrunning areas amounts to 1:200 to 1:100; that is, when the warm front on the ground is at the next place, - say, 100 km (62 miles) away, the warm air lies at a height of from 500 to 1,000 m (1,640 to 3,280 ft.). Any temperature rise over the cold air to above zero, depends on the height of the boundary area and the ground temperature behind the warm front. A 0.6° C. vertical temperature drop per 100 m (328 ft.) may be figured in the warm air. If the temperature in the warm-air zone rises, say, to 7° C., and the warm air over the port of take-off lies at 1,200 m height (3,937 ft.), the warm-air temperature here amounts to $7 - (12.06) = -0.2^\circ$ C. This means, however, that then the frostless wedge no longer extends over this point; that is, ice formed below cannot be made to thaw by climbing.

In reversed weather changes - that is, from mild to cold - supercooled rain may also cause serious ice accumulations, although such cases are fairly rare. They probably occur in the ratio of 1:100. Such meteorological conditions are illustrated in figures 8a, 8b, and 8c. The change is very sharply defined. There was a pouring rain in Mainz at 7 o'clock, at +8° C., accompanied by a strong wind from the west. It still poured at 8:30 o'clock, with just as strong northeast wind and -3° C. temperature. Subsequently, the rain changed to snow, the thermometer late in the afternoon registering 6° below. The severely supercooled morning rain caused a sudden and very heavy coating of ice on everything outdoors.

It is the same meteorological condition which in summertime is the forerunner of a thunderstorm. The cold air entered at an angle of 1° as established from the observation that the cold air influx on the Feldberg in the Taunus mountains and in Darmstadt, 40 km (24.9 miles) away, were simultaneous. The angle is slightly greater than with a warm-air influx; the slope of the area amounts to about 1:60.

Flight over the ice-forming layer would have been easily possible in this case, but not take-off or landing within the zone of supercooled rain, for with that abnormal density of rain, an airplane would have been rendered unfit for flying within two or three minutes.

Snow accompanied by rain outside of the clouds (meteorological conditions of figure 5) at sub-zero temperatures, is a sign that the warm-air wedge is still very flat. However, it is also possible that supercooled water droplets falling from above, freeze suddenly, for some reason, causing a slushy mixture of liquid and frozen droplets at one and the same time. In both cases the frozen precipitation is made to freeze by the liquid precipitation.

Hoar, frostlike ice accretion is observed when flying in very cold weather in clouds or even in cloudless, but very damp air. A specially identifying atmospheric condition is not given, although certain physical conditions must exist. The rime deposit usually occurs when the airplane is colder than the surrounding air as is generally the case during descent.

MEANS FOR PREVENTING ICE FORMATION

Horizontal Navigation

The best safeguard against ice deposit is to avoid the ice-forming zone by suitable horizontal or vertical navigation. The heaviest ice generally forms in long extended zones, which are bound to the "fronts," i.e., air mass boundaries. The synoptic maps give information about the location of such fronts. A flyer should never cross such an ice-forming front lengthwise, but at right angles, so as to shorten the hazard of ice accumulation (fig. 9). This horizontal navigation is, of course, not altogether satisfactory because a certain amount of ice formation still remains.

Vertical Navigation

Much better results are attainable by vertical navigation. According to figure 7, a pilot can fly in warm air and safe from ice from A to C, in spite of the supercooled rain, by choosing a favorable flying height; not even blind flying is necessary between A and B.

When flying in bad weather at below freezing temperatures at any height and in very damp cloud air, when ice accretion is probable as a result of new cold-air inflow or overrunning, the only way out is to try to climb above the clouds. This is often successful at 3,000 to 4,000 m (9,840 to 13,120 ft.) altitude, although it requires in most cases a height of 5,000 m (16,404 ft.) under such weather conditions. Many times even this height does not suffice. It is best to avoid, while gaining altitude, the zones where the front lies because there the ice deposit is heavier and, under certain circumstances, the climbing performance of the airplane falls short as a result of the incipient ice accretion and the ensuing poorer characteristics.

To overcome the different difficulties, a number of preventative devices have also been developed.

Methods of Prevention

The electric heating of venturis and pressure-head orifices is nearly always helpful in temperatures up to -12°. Distant-reading compasses and turn indicators are usually fitted to the engine; the antenna can be suitably protected. Control levers and such should be given a heavy coating of ambroleum. The cabin windows should be opened as soon as ice begins to form. To remove the ice from high-speed metal propellers, a short full throttle run is helpful. When the generator is frozen, operate the radio by storage battery or change to direct drive. The freezing of the carburetor assembly can be avoided by mounting the screen to the rear and installing exhaust heaters. Radiator shutters should be opened repeatedly and closed, although putting the shutter behind the radiator is better.

From the very considerable body of experimental work already carried out on the problem, the only practical preventative so far, is the Goodrich rubber-wing overshoe, fitted over the leading edge along the whole length requiring protection, by the inflation of one or more rubber inner tubes. The regular pulsation of the overshoe by compressed air enables the ice to be broken up and blown away in the wind.

BEHAVIOR WITH ICE DEPOSIT

If there is danger of ice formation the crew should, before undertaking the flight, be familiar with the condition of their airplane, with the total meteorological conditions, and the route, with the stress on <u>total meteorological conditions</u>, not the individual forecasts. Reliable meteorological predictions as to the probable encountering of ice conditions in flight and a knowledge of the extent of the area with, possibly, the shortest cut to safety, are necessary. If anything appears doubtful, the flight should be postponed.

The most unfavorable weather condition relative to icing, is that connected with a change of weather from frost to thaw. (The most dangerous range lies between cold and warm, in which a front with precipitation is formed.) The possibilities as to area are too vast to be enumerated here. Depending on area and energy of the front, the location of the points of departure and arrival with respect to it, and the possibility of flying above, through, or below it must be weighed. When mountain chains have to be crossed, the flight below or through is practically ruled out, because the lifting of the air masses on the windward side and of the clouds, produces strong condensation processes and severe ice formation. (According to experience, any attempt to fly over the front, must be with the expectation of finding it extending to 3,000-4,000 m - or, even to 5,000 m - in mountain ranges.) The decision to fly over the front, depends upon the location of the point of departure and arrival relative to it. If both lie outside, i.e., in front and behind it, an adequately equipped airplane with a good rate of climb should encounter no particular difficulties. If, however, one or both points lie inside the front, the following rules should be followed: Climb should be made at low speed. If there is no sign of its ceiling at from 2,000 to 2,500 m (6,562 to 8,202 ft.), or if so much ice has already formed that the performance has dropped, the attempt should be given up. A further climb is possible only when the temperature in the lower 500 m (1,640 ft.) above the ground is above zero, so that the ice is thawed again. The same applies to the glide: low speed, high rate of descent. It should further be borne in mind that dipping into the clouds with a supercooled airplane may cause instantaneous freezing.

The ice accumulated while passing through the clouds is lost by evaporation some time after getting above the clouds. Considering the moisture which may still exist directly above the clouds, it is advisable to go a few hundred meters higher. No high or extensive cumulus clouds encountered over the front should ever be flown through, as all such cloud formations are sure to produce instantaneous freezing.

In level country it is possible at times to pass between the clouds, particularly at from 600 to 1,000 m (1,968 to 3,280 ft.). As the precipitation before the front is usually in solid form from a higher overrunning layer, icing is mostly absent. But in the zone where the overrunning warm air is encountered and the precipitation is a mixture of rain and snow, the ice will form. From this point on the front should be crossed as nearly as possible at right angles, while carefully observing the temperatures. A few changes in flying height should soon afford the best air layer. Flying from warm to cold demands more precaution because no thawing can be anticipated later on. In level flight through the clouds the customary speed may be maintained because the time factor itself is in favor of freezing.

Apart from these fronts, the top of the clouds in wintertime rarely exceeds 2,000 m (6,562 ft.). When the atmospheric pressure is fairly high, it is very often accompanied by an extensive, bad meteorological condition of the following appearances:

Ceiling of clouds around 100 m (328 ft.)

Visibility, 1 to 2 km (0.62 to 1.24 miles) and less

Temperature approaching freezing

Occasional misting or sleeting

These are low-lying clouds, partially spoken of as high fog. The top of the clouds in this case is seldom higher than 800 to 1,000 m (2,624 to 3,280 ft.). Above it there are no clouds but a temperature reversal is usually encountered. Topping the clouds in this case is not difficult, although in the last 200 to 300 m (656 to 984 ft.) below the top, a heavy coating of ice begins to form. The approach to an airport should be made with this cloud top in mind; that is, the approach should be from low heights. In case of slight precipitation, the humidity in the lower strata is naturally higher - also due to accumulation. In such cases, where the lower strata are apt to contain considerable dampness, while at the same time the ice hazard exists, particular caution must be exercised or the flight should be postponed, especially if the approach is to be made by the zz method.

Whereas the building up of the ice deposit can readily be observed in daytime, it cannot be seen at night unless some object such as a small airfoil is mounted outside of the fuselage, within reach of the pilot.

The most dangerous kind of ice formation is, as already stated, the so-called supercooled rain or ice-rain. (The meteorologist defines ice-rain as a precipitation of frozen raindrops, i.e., ice grains which, in themselves, are harmless.)

An airplane encountering such supercooled rain, should leave the zone immediately, as to remain or attempt further flight, may spell disaster.

Rime, rain, or snow may cause ice accretion on the ground which should, as a general rule, be completely removed from the airplane and the controls checked as to their operation.

The meteorological aspects described herein are largely those prevailing in Central Europe or in zones with similar climatic conditions.

Translation by J. Vanier,
National Advisory Committee
for Aeronautics.

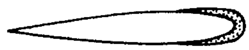


Figure 1.- Ice formed on wing due to super-cooled water droplets.

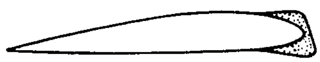


Figure 2.- Ice formation caused by super-cooled water droplets accompanied by solid precipitation.

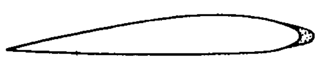


Figure 3.- Ice accretion with small form change, produced at very low temperatures.

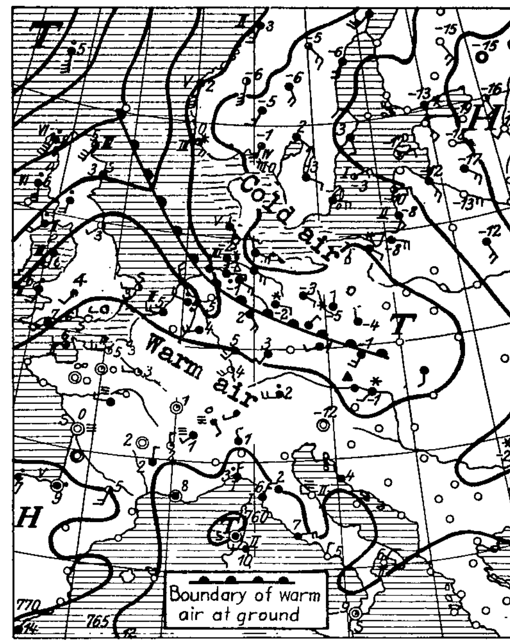


Figure 5.- Meteorological conditions with over-running hot air.

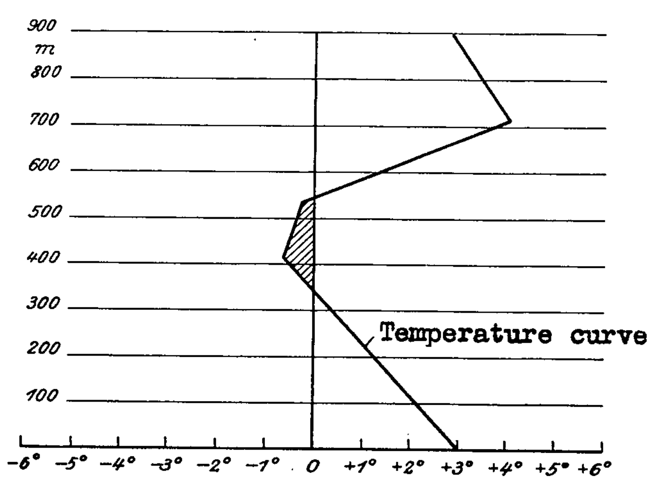


Figure 4.- Temperature grading with only very thin ice layer.

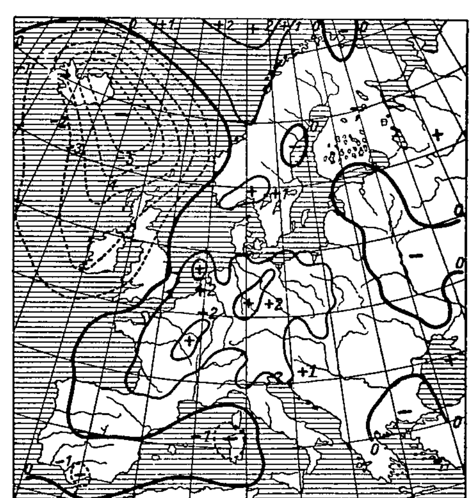


Figure 6.- Atmospheric pressure change corresponding to Fig. 5.

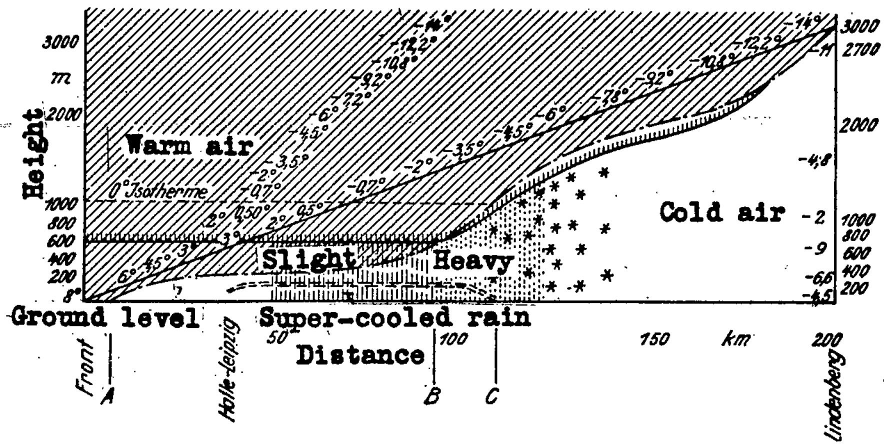


Figure 7.- Section through air masses according to Fig. 5 with ice forming zone.

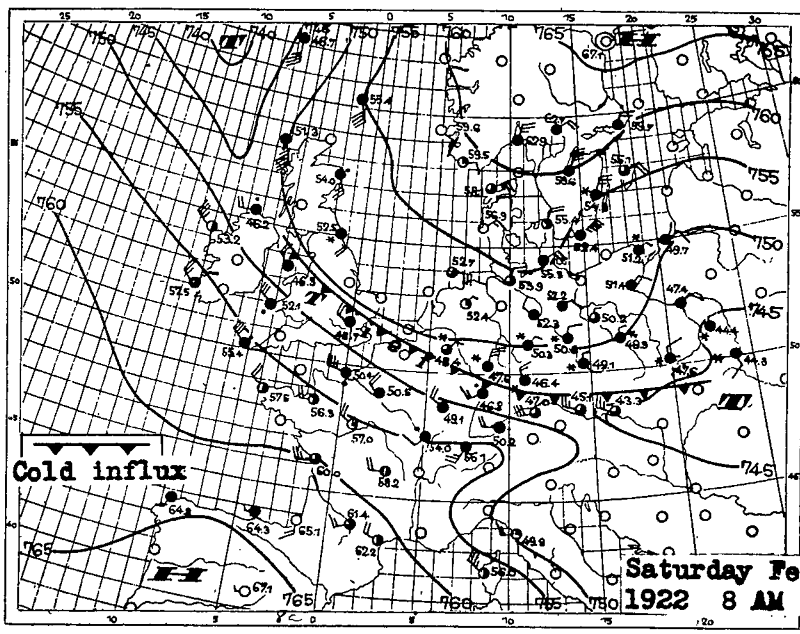
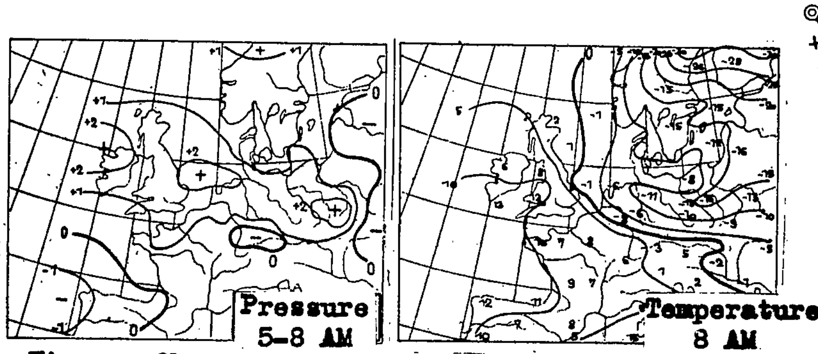


Figure 8a.- Weather conditions with ice formation due to super-cooled rain characterized by sharp cold air influx.



Figures 8b,c.- Temperature-pressure change for Fig. 8a.

Wrong
Good route
Best "

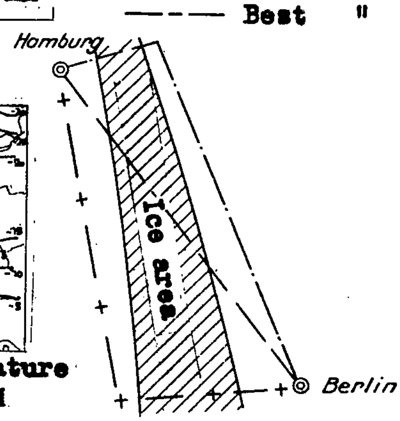


Figure 9.- Right and wrong method of crossing ice area.